

Magnetohydrodynamic waves driven by p -modes

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Abstract. Waves are observed at all layers of the solar atmosphere and the magnetic field plays a key role in their propagation. While deep down in the atmosphere the p -modes are almost entirely of acoustic nature, in the upper layers magnetic forces are dominating, leading to a large variety of new wave modes. Significant advances have been made recently in our understanding of the physics of waves interaction with magnetic structures, with the help of analytical theories, numerical simulations, as well as high-resolution observations. In this contribution, we review recent observational findings and current theoretical ideas in the field, with an emphasis on the following questions: (i) Peculiarities of the observed wave propagation in network, plage and facular regions; (ii) Role of the mode transformation and observational evidences of this process; (iii) Coupling of the photosphere, chromosphere, and above by means of waves propagating in magnetic structures.

1. Introduction

Solar p -modes are generated by turbulent convection just beneath the photosphere and propagate through the solar interior [5; 53; 54; 94; 116; 120; 160; 161]. They also leak power to the atmospheric layers – photosphere, chromosphere and corona – and interact with magnetic structures present in these layers. Since the force balance changes with height from a gas pressure dominated region below the photosphere into a magnetically dominated region in the corona, the nature of waves changes as well and mode transformation occurs. These p -modes leaking to the upper atmosphere are a possible source of chromospheric/coronal heating. Besides, measuring and modeling the wave properties provides us with sensible indicators of the thermodynamic and magnetic structure of the atmosphere where they propagate [2; 30; 51; 115]. This article reviews the current advances in the field of atmospheric waves and oscillations driven by solar p -modes with an emphasis on their interaction with local magnetic fields.

Observationally, sunspot waves have been a usual and relatively easy target, due to the clear influence of the strong sunspot's magnetic field on them. Photospheric waves in the umbra and penumbra have been detected over decades, as well as their propagation to the chromosphere in the form of umbral flashes (see e.g., [1; 15; 16; 27; 32; 33; 45; 96–98; 100; 101; 103; 104; 144; 166; 167], and many others). Sunspot magnetic fields are easily detectable via polarimetric measurements by many instruments [10], and the measured parameters of oscillations and of the magnetic field can be linked. The general aspects of physics of these waves (such as the different types of waves, their physical properties, the conditions requires for transforming one into the other, etc.) are relatively well understood nowadays (for reviews on sunspot waves before 2008, see [9; 81]). Numerical modeling of sunspot waves has helped to explain many details [8; 18; 19; 25; 45–47; 55; 77; 78; 82; 83; 85; 86; 113; 114; 127–129; 142; 143; 152].

Observations of waves in quiet regions have achieved important advances as well. Multi-line multi-layer observations have put in evidence how the propagation of waves in plage and network areas, and even in the quiet Sun, is influenced by the magnetic field (see, e.g., [29; 31; 48–50; 88–91; 106; 111; 131; 135; 158; 159; 169; 170], and references therein). Unlike in sunspots, magnetic field in the quiet regions is generally weaker, less organized, and, as a consequence, is more difficult to measure [151]. The question of the coupling between the different solar layers by means of waves, propagating in quiet Sun’s structures, is particularly interesting. Waves with photospheric periodicities are systematically observed in the solar corona [112]. Nevertheless, it is still an open question how to get the p -mode energy efficiently up there because of a set of obstacles that waves encounter on their way up, such as: cut-off layer, wave speed gradients, transition region, etc (see, e.g. [57; 118]).

Yet another interesting topic is the practical application of the theoretical knowledge to infer information about the wave modes from observations. Diagnostics based on polarimetry or filter imaging have their advantages and shortcomings, and the information is often masked by radiative transfer effects and limited spatial and temporal resolution [4; 76; 121; 122; 148; 154]. Analytical/numerical modeling and Stokes diagnostics should be applied hand by hand to disentangle information about the wave modes and calculate wave energy fluxes, or to infer the parameters of magnetic structure, for example.

All these topics are discussed below with an emphasis on wave propagation in network, plage and facular regions and their interaction with magnetic elements present there, leaving aside sunspot waves. Both observational and theoretical/numerical aspects are highlighted.

2. Observations of waves in quiet Sun’s magnetic structures

Magnetic elements in the quiet Sun are extremely complex and dynamic. Weak inter-network magnetic elements move, merge and cancel out, and small scale loops emerge on granular scale [3; 28; 69; 70; 105; 125; 126; 137; 150; 151]. Stronger magnetic elements in the network are generally more organized. Some recent works were able to resolve a network tube structure, including its canopy, from spectropolarimetric observations by Sunrise/IMaX [93; 107]. These real tubes are dynamic and asymmetric structures, unlike the “canonical” axisymmetric flux tubes used in many theoretical wave studies. Locally, acoustic p -modes and convective motions can drive waves in magnetic concentrations present over the quiet solar surface.

2.1. Network and inter-network regions

It has long been known that waves of 3-minute periodicity dominate quiet internetwork chromospheric regions [36; 67; 99; 102; 149]. These waves have been observed as bright intermittent Ca II H₂V and K₂V grains and are recognized to be acoustic shocks [26].

At the bright network cell borders, long period oscillations of 5–20 min are usually detected in the photosphere. These oscillations maintain their periodicity in the chromosphere and at larger heights [7; 91; 99; 131; 164; 169]. Shock occurrence is lower at the network cell borders compared to cell centers and the amplitudes remain below 2–4 km s^{−1} in the chromosphere.

Three-minute chromospheric oscillations inside supergranular network cells are well correlated with the underlying photospheric oscillations [36; 99]. It is not clear if the same happens to the 5-minute oscillations at the bright cell borders. Some earlier studies report that the correlation is difficult to trace [99], while others find a good correlation between the signals at two heights, suggesting nearly vertical wave propagation from the photosphere to the chromosphere in the proximity of the network magnetic elements [36; 95; 169]. Larger phase shifts between velocity signals at different heights, ϕ_{VV} , are found for waves at the network borders compared to cell centers [36; 95].

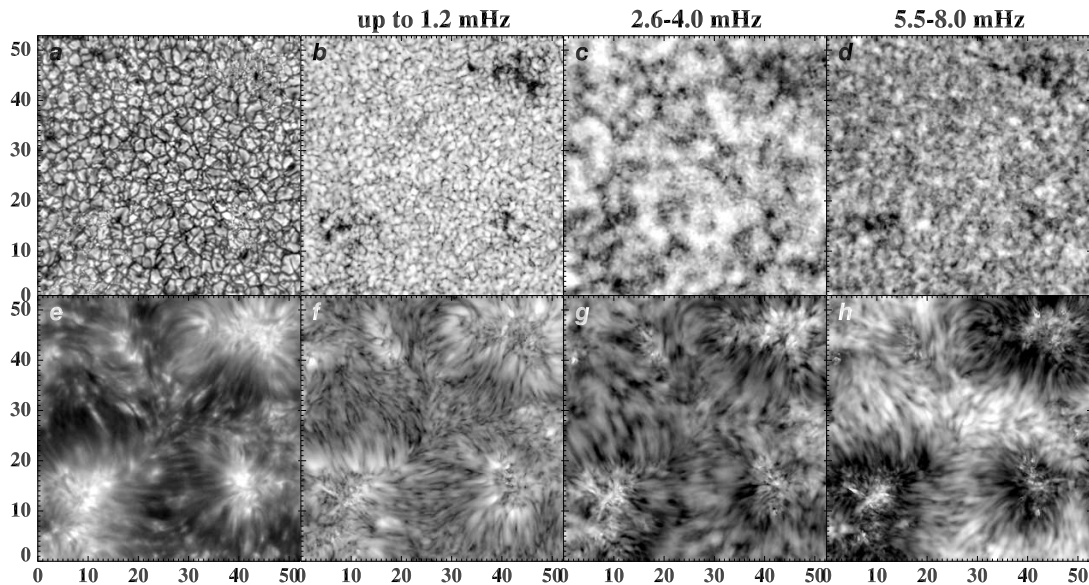


Figure 1. Example of IBIS observations of magnetic shadows from [169]. **a:** Speckle reconstructed broadband continuum at 710 nm for the FOV under analysis. **e:** Line core intensity of CaII 854.2 nm. **b–d** and **f–h:** Spatially resolved Fourier’s velocity power maps, averaged over the range of frequencies indicated. The intensity scale is logarithmic, with bright indicating larger Fourier amplitudes. **b–d:** photospheric Fe I 709.0 nm line. **f–h:** chromospheric Ca II 854.2 nm line. *Courtesy of G. Cauzzi.*

Recent high-resolution observations from space and ground-based instruments revealed a much richer behavior of network oscillations related to the magnetic field topology. It was discovered that short-period waves (3 min range, $\nu = 5–8$ mHz) propagate from the photosphere to the chromosphere only in restricted areas of the network cell interiors, and that spatial distribution of 3-minute chromospheric shocks is highly dependent on the local magnetic topology [169; 170]. Network magnetic elements are surrounded by “magnetic shadows” where the power of short-period waves is reduced [48; 49; 74; 91; 136]. An example of this result borrowed from [169] is given in Figure 1. A prominent feature of these observations is the fine structuring of power maps at different frequencies, following the structure of chromospheric mottles.

Long-period waves (5 min range, $\nu = 1.2–4$ mHz) propagate efficiently to the chromosphere in the close proximity of the magnetic network elements, forming *enhancements* on the power maps (“power halos”) [88]. These long-period network halos are most prominent in the photosphere, but are also present in the chromosphere; and are observed to be co-spatial with chromospheric “magnetic shadows” for 3 min waves. The halo/shadow areas show positive ϕ_{VV} phase shifts indicative of upward propagating waves at 3 min periodicity, but a mixture of positive and negative phase shifts for larger-period waves of 5–7 min, with a good coherence in all cases.

The peculiar power distribution in halos/shadows is apparently linked to the height of the magnetic canopy, defined as a layer where the plasma $\beta = 1$ [89; 90; 108; 109]. At the close proximity of network elements, where the canopies are low-lying (below 1600 km), the *chromospheric* power of short-period (3 min) waves was found to be suppressed, and the *photospheric* power of long-period waves (5–7 min) was found to be enhanced [89; 90]. It was

suggested that the 5-7 min power enhancements in the photosphere may be due to reflection of waves on the overlying canopy. These enhancements are observed at all magnetic field inclinations, but are specially significant for more inclined canopy fields at the close proximity of magnetic elements, suggesting more efficient mode conversion there [89].

Table 1 summarizes the properties of oscillations in the quiet network areas, in terms of their periods.

2.2. Plage and facular regions

Plage and facular regions contain larger magnetic flux structures compared to the network regions discussed above. Early works (based on slit spectra) showed that the amplitude of 5 min oscillations in the photosphere decreases by about 25% in plage regions with an average flux above 80–100 G, compared to the quiet Sun, while shorter-period oscillations strengthen [6; 35; 68; 175]. More recent spectropolarimetric observations confirm that the amplitude of 5-min oscillations decreases by 20-40% in the facula photosphere [87]. These observations also reveal that the power of 5-min oscillations increases significantly in the chromosphere, dominating the power spectrum [29; 87]. The phase spectra of the 5-min facular waves are compatible with the vertical wave propagation from the photosphere to the chromosphere. One may conclude then, that the dominance of 5-min periodicities in the chromosphere is a common feature of both network and plage waves. However, the picture does not seem to be that simple.

The 2D filtergram observations show more pieces of the puzzle regarding the power distribution for long-period waves in relation to the magnetic field topology. It was argued that inclined magnetic field lines at the boundaries of large-scale enhanced network cells provide “portals” through which long-period (5 min) waves can propagate into the solar chromosphere, due to the lowering of the cut-off frequency in the low- β environment [58; 73; 110; 132; 133]. Larger propagation speeds of chromospheric waves were indeed found for strong fields inclined more than 40 degrees. At the center of plage magnetic elements (where the field is expected to be close to the vertical) preferably 3 min oscillations are observed to be transmitted to the

Table 1. Periods of network & inter-network oscillations

	Centers of mag. elements	Close surroundings	Inter-network beyond mag. elements
Photosphere	5 min	5 min	5 min
Chromosphere	Possibly 5 min	5 min enhanced 3 min shadowed	3 min shocks
Propagation	Up & down	Up & down	Up

Table 2. Periods of facula & plage oscillations

	Centers of mag. elements	Close surroundings	Halo areas
Photosphere	5 min damped 3 min enhanced	5 min damped 3 min enhanced	3 min enhanced
Chromosphere	Not clear	5 min for inclined B	3 min enhanced
Propagation	Possibly up	Possibly up	Up and down

chromosphere, while 5 min oscillations were transmitted at the edges of plage magnetic elements, where the field expands and becomes inclined [174].

The 2D filtergram observations rely on potential extrapolations from photospheric longitudinal magnetograms, unlike spectropolarimetric observations where the inversion of Stokes profiles gives information about the photospheric magnetic field vector (see e.g. [29]), suggesting it to be essentially vertical and thus giving strong arguments for the vertical propagation. On the other hand, 2D filtergrams have much higher resolution and field of view needed to detect the inclined propagation, if it takes place. The advantages of both observing techniques (imaging and spectropolarimetry) were exploited in [158; 159], by using simultaneous IBIS photospheric and chromospheric measurements together with spectropolarimetric inversion of the SOT/Hinode data. For a plage region containing a pore, maximum transmission of 3 min oscillations was found for field inclined by 15 degrees, while 5 min oscillations were transmitted for the field inclined by 25 degrees, providing support for the inclined propagation of long-period waves, at least for the strong field of a pore. It is not clear, however, if the same happens for the weaker magnetic elements, and more data as those by [158; 159] are clearly needed.

For shot-period waves (3 min range, $\nu = 5.5 - 7.5$ mHz), the power distribution over plage regions shows a suspicious enhancement, both in the photosphere [14] and in the chromosphere [11; 165]. These power enhancements are known as “halos” and have been much discussed in the literature on local helioseismic waves¹. The acoustic power measured in halos is higher than in the quiet Sun by about 40-60% [12; 38; 66; 72; 117]. The halos are observed at longitudinal magnetic fluxes $\langle B \rangle = 50 - 300$ G [66; 72; 162]. In the photosphere the halos are located at the edges of plage regions, while in the chromosphere they extend to a large portion of the nearby quiet Sun [11; 14; 162]. The characteristic period of maximum enhancement decreases with field strength and the wave spectrum in halos is shifted to higher wave numbers at constant frequency [52; 153]. The wave power in halos is observed to be modulated with the field inclination, being stronger for more inclined fields [153]. The height-dependent changes in halo properties seen in HMI/AIA SDO data provide signatures of magneto-acoustic wave refraction sensitive to magnetic field strength and topology [135] (the presence of up and down-going waves has also been reported previously by [13]).

The vast amount of information on the observed halo properties is mostly obtained from the observational datasets typical for local helioseismology (i.e. long time series over a large portion of the Sun, including a complete active region, but medium spatial resolution, as SOHO/MDI or SDO/HMI). It is not clear how to consistently compare these large-scale data with higher resolution (but smaller area) IBIS, SST and Hinode data [58; 131; 158; 159; 174] or chromospheric/transition region TRACE data [73; 110; 132; 133], resolving propagation in individual magnetic structures. In addition, there is much confusion about the waves observed in plage, facular, or enhanced network regions, often discussed in the same context. It is not evident beforehand if the observed wave behavior should be the same, since the field strength of the magnetic structure definitely plays a crucial role.

Table 2 makes an attempt to summarize the properties of oscillations in plage areas, though definite conclusions are hard to derive in some cases.

2.3. Magnetic field oscillations

Up to here, we have discussed oscillations of velocity and intensity. Magnetic field measurements, when performed, were mostly done to obtain the magnetic topology, but not oscillations of the magnetic flux (or magnetic field vector) itself.

Even in strong sunspot regions it has been hard to detect magnetic field oscillations due to

¹ Note that halos in plage are observed at short-periods, unlike long-period power halos surrounding network magnetic elements, discussed in Section 2.1.

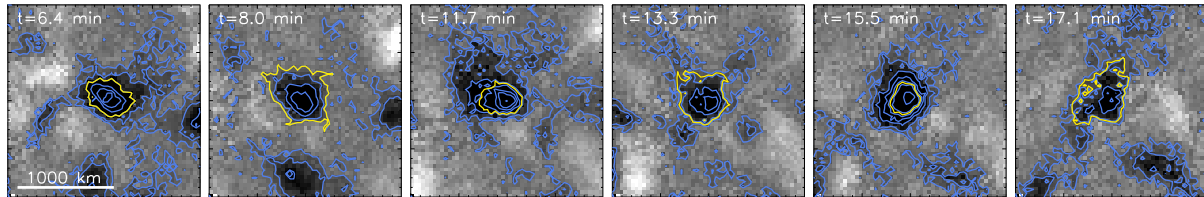


Figure 2. Example of time evolution of a weak circular polarization patch in the quiet Sun from [106]. The black and white background represents the magnetic flux density computed in the weak-field approximation, saturated to $\pm 20 \text{ Mx cm}^{-2}$. Yellow line is the iso-magnetic flux density contour containing a time-constant magnetic flux of $-5 \times 10^{16} \text{ Mx}$. *Courtesy of M. Martínez González.*

the smallness of the expected amplitudes and due to radiative transfer and instrumental effects, masking the real oscillations [76; 87; 122; 147; 148; 154].

The detection of magnetic flux/field oscillations due to magneto-hydrodynamic waves in the quiet regions has been elusive. The relations between the magnetic flux, velocity and intensity oscillations in the photosphere of pores and intergranular magnetic elements, obtained from homogeneous, seeing-free SOT/Hinode data, reveal root-mean-square amplitudes of magnetic flux fluctuations of 4–17 G (0.3%–1.2% from the background value), corresponding to velocity oscillations of $\sim 100 \text{ m s}^{-1}$ and intensity oscillations of 0.1%–1% [50]. Velocity was leading the magnetic flux oscillations by a quarter of cycle, and magnetic flux oscillations were 180 degree out of phase with the intensity oscillations. These phase lags were interpreted as due to superposition of the ascending and the descending sausage and kink mode waves reflected at the transition region [50].

Another recent detection of oscillations of magnetic flux density in quiet Sun magnetic elements was done from high-resolution Sunrise/IMaX data [106]. It was discovered that the area of patches with constant magnetic flux oscillates in response to granular forcing in a range of periods similar to granular life times (implying that magnetic field strength oscillates in antiphase). An example of such observation borrowed from this work is shown in Figure 2. Curiously, the amplitude of these area oscillations is highly non-linear with more than 100% variations from the mean value. No apparent correlation with velocity or intensity oscillations was found.

3. Models

This section gives an overview on recent, mostly numerical, models of the wave propagation in solar magnetic structures. We subdivide the simulations into several (overlapping) groups, one of them aiming to explain the power distribution in and around magnetic features, another group studying the energy propagation by waves from the photosphere to the chromosphere, transition region and corona, yet another one for the mode conversion.

3.1. Coupling of the photosphere, chromosphere and above

Small-scale magnetic field concentrations are ubiquitous in the quiet Sun and magnetic waves driven in these elements by p -mode or granular forcing are obvious candidates to transport energy to heat the upper layers. Solar magnetic elements are far more complex than canonical axisymmetric flux tubes. But despite the clear simplifications of the tube structure, theoretical works on propagation of waves in flux tubes are of great importance to understand the basic physics of the wave mode behavior in small scale magnetic elements. There have been numerous analytical works using the thin flux tube approximation, when the radius of the tube is considered

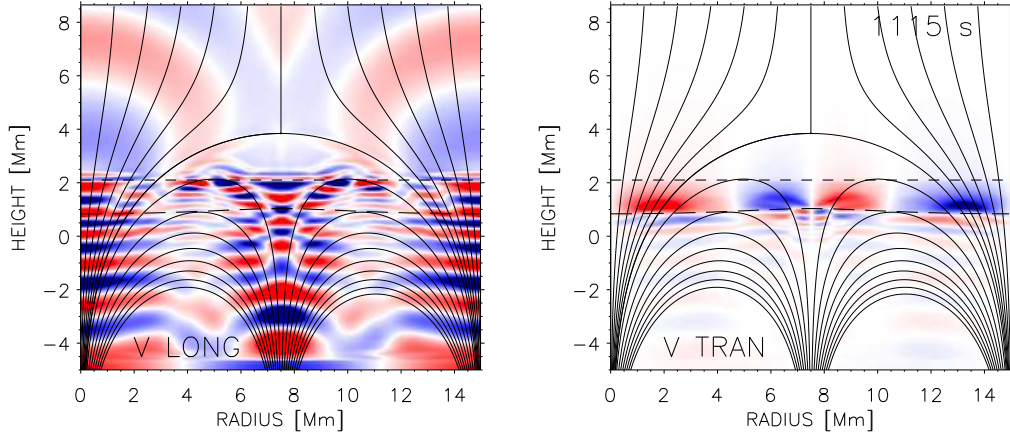


Figure 3. Snapshot of longitudinal (left) and transversal (right) velocities, scaled by a factor or $\sqrt{\rho c_s}$ and $\sqrt{\rho v_a}$, correspondingly, in the 2D simulations of fast (acoustic) mode propagation and conversion from sub-photosphere to the low corona from [24].

to be much smaller than the local vertical scale height, and the internal flux tube structure can be neglected [17; 37; 40; 138–141; 145; 146; 157] (see [155; 156] for a review). In fact, the comparison to simulations of magneto-convection suggests that a second-order thin flux tube approximation might do reasonably well for super-equipartition magnetic field concentrations like those existing in the simulations [176]. This argument can be used for wave studies if asymmetry and flows are not crucial for the considered problem.

The number of idealized simulations of flux tube waves propagating from the photosphere to the chromosphere and above is ever increasing during the last several years [41–43; 59–63; 75; 79; 123; 171–173]. Different ways of driving flux tube waves have been checked: horizontal motions producing transverse kink waves; pressure fluctuations producing longitudinal waves; twisting motions generating torsional Alfvén waves; observationally-driven or impulsive motions. The general idea behind all these works is to understand how much of the wave energy can reach the chromosphere and corona, and whether the wave modes reaching there can be easily dissipated to convert their energy into heat (as, e.g. compressible acoustic modes).

The transverse foot-point driving was extensively studied in a series of papers [60–62; 171; 173] by means of 1D and 2D simulations. These works mostly aim at explaining waves in bright network elements at cell borders observed in Ca II H (see Section 2.1) and their relation to G-band bright points. It was discovered an efficient mechanism of non-linear coupling between the kink waves (generated by transverse foot point driving) and longitudinal waves, forming shocks and supplying energy to the chromosphere. The efficiency of the coupling was found to be a function of the plasma β , being maximum for tubes with $\beta = 0.2$ when the kink and tube wave speeds are equal [61]. Adding a second dimension to the modeling (2D), the transverse foot point motions were seen to excite fast and slow magneto-acoustic waves inside the tube, and acoustic ones at the interface between the tube and the non-magnetic medium [62]. The acoustic waves at the interface steepen to shocks in the chromosphere and flux tubes with stronger magnetic field produce these shock waves more efficiently [171].

The above works were mostly focused on short-period (10–20 sec) waves or impulsive driving, and it is hard to make a direct comparison to the observations. Nevertheless, similar processes of magneto-acoustic mode generation and transformation were shown to take place when considering more realistic driving with 3 and 5 min periodicities [79]. Complex shock wave

patterns are formed across the tube, with shock waves propagating alongside the tube borders. Sub-arcsec spatial resolution would be needed to observationally resolve this pattern [84; 172].

Apart from linear and non-linear mode transformation, slow chromospheric shocks in magnetic flux tubes were demonstrated to be produced by a mechanism of “turbulent pumping” [75], i.e. “massaging” of the magnetic tubes in intergranular lanes by external downflows. Possibly, a similar process is responsible for the periodic area variations of quiet Sun magnetic elements discovered in [106].

When the tube foot points are twisted instead of being transversally shaken, torsional Alfvén waves can be generated. There are indications that the energy input into the chromosphere is lower for the twisting driver, compared to the transverse shaking [173]. The torsional Alfvén waves, generated by twisting driver seem to be frequency-filtered by the tube’s three-dimensional structure, with higher frequencies transmitted at the central part of the tube, and lower ones at the sides [42].

The next challenge for the wave numerical modeling in 2D and 3D is to extend the analysis into the transition region and corona, in order to explain how waves with photospheric periodicity leak their energy to the upper atmosphere. This is numerically challenging, since many pressure scale heights have to be modeled at the same time, and the wave speeds change considerably. The transition region represents a discontinuity in the wave speed and waves are expected to be efficiently reflected there. Thus, it is unclear how much energy can go through. Nevertheless, short-period (30 sec) magneto-acoustic waves were shown to be transmitted rather efficiently through the transition region, exciting horizontally propagating disturbances there [43]. Figure 3 shows an example of the modeling of wave propagation from the sub-photosphere to the chromosphere, transition region and corona for realistic periods in the 3-5 min range [24]. It demonstrates a complex wave pattern formed by multiple mode transformations at the $\beta = 1$ layer, wave refractions and reflections at the transition region and a 2D magnetic null point located above. More work will be needed in the future to quantify these complex interactions, and to evaluate the transmitted energy, depending on the magnetic field configuration and strength.

3.2. Mode transformation in 2D and 3D

Linear mode transformation is an important process that enables different wave modes to exchange their energy when their propagation speeds are close. Mode transformation between fast and slow magneto-acoustic modes in 2D was extensively studied analytically and numerically [8; 18–21; 34; 77; 142; 152; 178]. A review on these works before 2008 can be found in [81]. In brief, the direction and the effectiveness of the mode transformation depends on the wave frequency and the attacking angle between the wave vector \vec{k} and the magnetic field \vec{B} at the layer of plasma $\beta = 1$. The fast-to-slow mode transformation is complete for waves with $\vec{k} \parallel \vec{B}$. The fast-mode high- β waves launched from their sub-photospheric lower turning points typically reach the transformation layer with an angle close to 20–30 degrees, so the transformation is particularly strong for magnetic fields inclined by this amount [21; 34; 152].

Recently, mode transformation in 3D has attracted a lot of attention. It enables to produce Alfvén waves from fast magneto-acoustic waves above their reflection height in the low chromosphere, a mechanism that may allow to transport wave energy through the transition region to the corona. Alfvén waves are claimed to be detected by numerous observations, but the discussion on the nature of the detected waves is still ongoing [112; 130; 134; 163; 168].

The pioneering study of 3D mode conversion from fast to Alfvén waves for homogeneous inclined fields discovered it to be most efficient for preferred magnetic field inclinations between 30 and 40 degrees, and azimuth angles between 60 and 80 degrees [22]. This orientation allowed the best alignment with \vec{B} of the fast mode wave propagating from its sub-photospheric lower

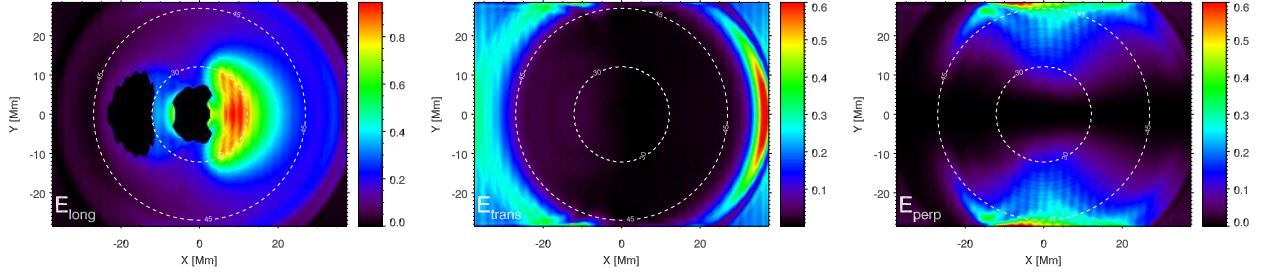


Figure 4. Example of wave energy fluxes in the chromosphere of a sunspot model from [47] showing the redistribution of the energy of different modes due to three-dimensional mode conversion. Left panel: acoustic flux due to slow longitudinal waves; middle panel: magnetic flux due to fast waves; right panel: magnetic flux due to Alfvén waves. The units of the color coding are $10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$. *Courtesy of T. Felipe.*

turning point. Alfvénic fluxes transmitted to the upper atmosphere are found to be similar, or larger, than acoustic fluxes at some orientations. Low-frequency gravity waves can also be converted efficiently into Alfvén waves at large magnetic field inclinations [118].

While the fast-to-slow mode conversion occurs at the layer where plasma $\beta = 1$, the fast-to-Alfvén conversion takes place around and above the fast wave reflection height z_{ref} in 3D (see Fig. 1 in [86]), localized more closely to z_{ref} as the frequency increases [23]. For 3-5 min waves, the conversion process is typically spread over much of the chromosphere. Both up-going or down-going Alfvén waves can be produced depending on the relative orientation of the wave vector and magnetic field at heights where the fast mode undergoes the refraction, going up and down [23; 86].

Numerical simulations of conversion to Alfvén waves require 3D or, at least, 2.5D geometries [44; 47; 85; 86]. Recent 2.5D simulations show that the global picture of conversion to Alfvén waves remains valid when considering complex field configurations, appropriate for large-scale sunspot magnetic structure [86]. The conversion to Alfvén waves is particularly important for strongly inclined fields like those existing in sunspot penumbrae. A fully 3D simulation, covering a large portion of a sunspot model with a wide range of inclinations, nicely demonstrated that a significant energy flux due to Alfvén waves can indeed be transmitted to the chromosphere at large field inclinations [47]. The upward-propagating flux due to Alfvén waves at the peripheric parts of the sunspot model was found to be as large as the acoustic flux due to slow longitudinal waves propagating close to the axis. An example of this result is shown in Figure 4.

Inclusion of radiative losses into the model does not change significantly the wave paths neither the conversion picture [119].

3.3. Tunneling of 5 min oscillations to the chromosphere

A specific question for the models of wave propagation in small scale structures is the explanation of the power spectrum of waves at chromospheric heights (see Section 2). Observations in network regions mostly agree that long-period 5 min oscillations are transmitted to the chromosphere in the close proximity of network magnetic elements (Section 2.1). In a plage, it seems not clear yet whether these long-period oscillations are transmitted at the plage borders with predominantly inclined field or vertically from the photosphere (Section 2.2).

There have been a number of works arguing that inclined magnetic field at the boundaries of enhanced network and plage regions allows long-period slow acoustic waves to propagate into the solar chromosphere due to a reduction of the cut-off frequency [58; 73; 110; 132; 133]. Numerical 1D modeling confirms the efficiency of this mechanism [64]: long-period 5 min waves

can only propagate upwards where the magnetic field is inclined, whereas waves with periods around 3 min dominate when the field is vertical. This modeling includes a complex treatment of radiative transfer, but simplifications of a one-dimensional propagation in a constant inclined field.

Alternatively, some authors proposed that radiative losses in thin flux tubes can help propagating long-period oscillations vertically upward [29; 80]. The presence of radiative losses can lead to a significant reduction of the cutoff frequency, formally adding a propagating component to the oscillations [140]. Two-dimensional simulations of flux tube waves with a 5 min periodic photospheric driver, and including radiative losses by means of a simplified Newton's law with fixed radiative relaxation time, demonstrate the effectiveness of this mechanism in leaking 5 min oscillations into the chromosphere inside vertical flux tubes [80]. The power and phase spectrum of waves in these simulations reproduce observations in facular regions [29].

The treatment of radiative losses by Newton's law [80] is very rough. Recently, realistic radiative magneto-convection simulations were performed in a model extending from the convection zone to the corona, where oscillations were produced self-consistently by the turbulent motion in the convection zone without any imposed external driver [65]. A sophisticated state-of-the-art treatment of radiative losses was included. The simulations aimed at quantifying the contribution of both effects - field inclination and radiative losses - into the resulting spectrum of waves at chromospheric heights. It was found that 5 min oscillations are able to propagate in regions where the field is inclined and strong, including the edges of otherwise vertical flux tubes, whereas in regions where the field is vertical (center of flux tubes) or weak, oscillations with periods around 3 min propagate [65]. Radiative losses were found to play only a minor role in determining the propagation spectrum (though no reference simulation with radiative transfer switched off was performed).

There are also alternative mechanisms for transmission of 5 min oscillations into the chromosphere, by means of non-linear photospheric pulses that create nonlinear wakes leading to a trail of consecutive shocks with 5 min periodicity [177].

3.4. Power distribution at different frequencies

Many recent studies agree that the peculiar power shadowing and enhancements observed in plage and network areas are related to processes of mode conversion and refraction at the inclined magnetic canopy in the proximity of the $\beta = 1$ layer (see Sections 2.1 and 2.2).

There have been numerous theories to explain high-frequency acoustic halos in plage regions [11; 14; 55; 66; 71; 72; 82; 92]. Numerical simulations of interaction of waves with sunspot/plage flux tubes suggest that the power enhancement in halos is produced by mode mixing induced by the magnetic field, resulting in preferential scattering from low to high wave numbers [56]. Alternatively, an explanation has been offered based on the enhanced high-frequency wave excitation at the regions of intermediate magnetic field strength in halos [71].

Single-source numerical simulations of magneto-acoustic wave propagation in a magneto-static sunspot model demonstrate that the halo effect happens in a natural way due to the additional energy input from the high-frequency fast mode waves, after their refraction above the $\beta = 1$ layer [82]. The frequency and location of the halo is extremely sensitive to the relative location of the $\beta = 1$ layer, the cut-off layer and the formation height of a given observed spectral line. The halo is produced in those photospheric regions where the field is intermediate, implying that the Alfvén speed is lower than the sound speed. The halo is not observed at low frequencies because these waves are already reflected by cut-off below the transformation layer, and is not observed in the umbra of the sunspot because the refraction happens below the layer visible to spectral line observations. This model [82], as well as the model of mode mixing [56] suggest that the halo power enhancements might be larger in the horizontal velocity component.

To clarify the nature of magnetic shadows, numerical simulations of high-frequency magneto-acoustic wave propagation in a snapshot of a three-dimensional model of magneto-convection were carried out [124]. On their way up, acoustic waves were converted into different mode types and were refracted. The Fourier analysis of this simulation clearly shown chromospheric shadows, similar to the observed ones. It was concluded that these shadows are linked to the mode conversion process and that power maps at these heights show the signature of the different magneto-acoustic wave modes. Yet another mechanism to explain power enhancements in halos was proposed based on acoustic waves trapped in field-free atmospheres lying below small-scale magnetic canopies of network cores and active regions [92].

Alternative pictures of wave transformation and refraction [82; 92; 124] are, in fact, similar, suggestive that both, halos and shadows, are different manifestation of the same physical mechanism. Recent observational results seem to favor the model based on wave transformation and refraction as well [135]. One can not exclude, though, that other effects may also play a role [56; 71]. For example, acoustic halos are found to be co-spatial with acoustic glories, locations with enhanced seismic emission surrounding active regions [39]. The nature of the glories is different to halos, since they tell us about an increase of seismic emission, i.e. power of waves emanating directly from the wave sources, whereas the acoustic halos are just measures of increased wave amplitudes, whatever is the reason. Thus, the last word on the nature of halos is not yet said.

4. Conclusions

Significant advances have been made in our understanding of the physics of atmospheric waves and their interaction with local magnetic structures in the photosphere, chromosphere and above. Summarizing the vast amount of theoretical and observational works reviewed here, we give below some brief conclusions and suggestions for perspective future work directions:

- The observed distributions of photospheric and chromospheric power of long and short period waves seems to be distinct over network and plage/facular regions. In the network, long-period 5 min waves seem to be transmitted in the close proximity of magnetic elements, while short-period 3 min waves are “shadowed” due to the interaction of magneto-acoustic waves with the more horizontal fields of the canopies. In the stronger-field plage regions, short-period (3 min, $\nu = 5 - 7$ mHz) halos dominate both in the photosphere and in the chromosphere, and the propagation of long-period waves is enhanced for inclined fields, but vertical propagation has also been reported.

The reason for that different behavior may be the variation of the height of the magnetic canopy $\beta = 1$ layer, being lower for stronger plage fields, thus modifying the spectrum of waves reaching the heights sampled by photospheric and chromospheric observations.

More high-resolution studies are needed in this direction, comparing regions with different magnetic fluxes, both at the disc center and closer to the limb to get information about horizontal velocities. Simultaneous measurements of the magnetic field vector are also very important.

- On the theoretical side, there seems to be still no agreement on the explanation of the presence of ubiquitous long-period waves in the chromosphere above network bright points and plage. Different observations give evidences both for inclined and vertical propagation (both upward and downward), at least for the network elements, while theoretical models seem to point toward the inclined propagation as a dominant mechanism. Inclined propagation receives more observational support especially for the strong field plage regions where it is expected that the slow acoustic waves propagate field-aligned in the low- β regime. Future studies should address the propagation in weaker structures, accompanied by observations of more network and inter-network elements.

- There have been few detections of magnetic field oscillations in quiet solar regions reported in the recent literature. Magnetic field and flux oscillations are very hard to detect, but an effort should be made to increase the number of such studies, since the amplitude and phase relations between the magnetic field variations and other parameters give valuable information on the observed wave types.
- Idealized simulations of wave propagation from the photosphere to the chromosphere in small scale flux tubes are rather well developed. These models have suggested a number of mechanisms to transport the energy of the wave to the upper layers. Three-dimensional simulations are being developed. A remaining challenge is to couple the sub-photospheric layers, photosphere, chromosphere, transition region and corona by means of waves. This is needed to understand how (and what amount of) the wave energy can reach the corona, depending on the driver properties, and taking into account all the wave physics such as 3D mode transformation, refraction, reflection, non-linear interaction, as well as dissipation mechanisms. It will be interesting in the future to get more insights on the efficiency of conversion to Alfvén waves on inclined canopy fields of the quiet Sun small scale flux tubes, by means of 3D numerical simulations.
- Oscillations in the surroundings of quiet Sun magnetic structures in network, plage and facular regions are being observed at extremely high spatial resolution, and their relation to the magnetic topology is being clarified. Theoretical models for acoustic halos and shadows indicate that both may have a similar origin, tracing mode transformation process, and fast mode refraction and reflection at the inclined field of the magnetic canopy. It remains to clarify the relation between the acoustic halos and glories, present on the same locations. Some theoretical models for halos suggest that the power enhancement in horizontal velocity component should be significantly stronger than in the vertical one. In the future it will be interesting to study halos and shadows at locations off the disc center to shed more light on their nature. Models of transformation to Alfvén waves suggest they will be reinforced at the periphery of active regions. Checking this in future observations is important as well.

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